SIMULATIONS USING FORTRAN PROGRAM TO UNDERSTAND BUNCHING PHENOMENON IN LINACS

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Abstract

A Program in FORTRAN is written to simulate and understand the bunching phenomenon (hard bunching) in linacs and back bombardment of electrons to the electron gun (energy spread and percentage). It is a 1 D simulation using the ballistic single particle collisionless model and giving the output beam energy, phase bunching of the buncher cavities of the linac. The paper gives the logic of the program, the benchmarking, output results with the 3 buncher cavities of the 10 MeV Linac and optimization by changing the length of the first buncher.

INTRODUCTION

In an electron gun the electrons are accelerated by a high dc voltage V_0. These electrons pass through a buncher cavity with the gap voltage as $V_S = V_1 \sin(wt)$, where V_1 is the amplitude of the signal. It results in the variation in electron velocity and the electrons gradually bunch together as they travel the drift space after the RF gap. This is known as velocity modulation. In the case of klystrons, it is assumed that $V_1 << V_0$. But in the case of RF linacs $V_1 >> V_0$ and hence hard bunching takes place. An example is, for the 10 MeV RF Linac at EBC, V_0 = 50 kV and the electric field in the first buncher is 15 MV/m and the length of buncher is 45 mm, so V_1 = 675 kV.

The 10 MeV RF Linac structure of EBC is a 33 cell OACCL with 3 bunchers, 14 accelerating cells and 16 coupling cells and operating in $\pi/2$ mode of frequency 2.856 GHz. The electron injected into the accelerator structure thus goes through 33 RF cavities, of which it gains energy only in the 17 cavities and does not gain any energy in traversing the coupling cells. Buncher cavities bunch the electron beam to the correct phase for optimum acceleration. During the bunching process, some of the electrons get accelerated backward and hit the cathode of the electron gun.

ASSUMPTIONS AND PROGRAM LOGIC

To understand the phenomenon of bunching we use numerical methods with the assumptions: (a) 1 D problem, (b) ballistic single particle collisionless model, (c) no space charge, (d) energy of every particle entering the rf gap is constant eV_0, (d) particles move along the z axis (r = 0), (e) only Ez (r=0,z,t) = E_{Z0}(r=0,z).Sin(wt) component of electric field is considered and E_{Z0}(r=0,z) is constant in space in the beam hole of the rf buncher cavity, i.e., only longitudinal rf bunching considered and transverse effects ignored.

The injected electron phase is varied from 0 to 720 degrees (with $\Delta\Phi$ = 1 degree), which implies that a DC electron beam is injected into the linac structure for 2 RF cycles. Here, the RF time period is divided into very small fixed time step Δt. Then from energy of particle its relativistic factor γ and velocity factor β are calculated. The particle then traverses a distance $\Delta z = \Delta t\ \beta c$. While traversing this distance it sees a constant electric field. The value of this electric field is calculated by the amplitude and phase of the field in the rf cavity. The energy gain of the particle is then calculated using this electric field. The particle gains or loses energy depending on the phase of the electric field. The minimum energy of the particle is truncated to the thermal energy. The direction of the particle motion is conveyed by sign on its energy. From the latest energy of particle, γ and β are again calculated and using the new information of phase, the process continues, till the particle comes out of the rf cavity in either forward or backward direction. For particles coming out in the forward direction, calculations continue with the new set of parameters for the field, phase in the next rf cavity.

The FORTRAN program calculates the energy gained by the electron after each of the cavities. It also calculates the total no of accelerated electrons, at the end of the accelerator, out of the injected particles. The electrons accelerated backward are calculated only for the first buncher cavity as they hit the cathode. For the electrons accelerated backward in the other cavities and subsequently lost, their energy is set to zero. Thus we know how far inside the linac, an electron has traversed.

BENCHMARKING

The program was benchmarked with the parameters and graphs of single RF gap acceleration, given in the book "Electronic Irradiation of Foods" by R. B. Miller (Pages 165-167). The results closely match (see Fig. 1)

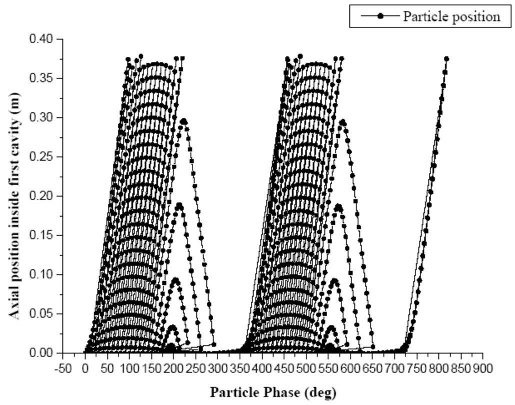

Figure1: Plot showing the bunching of particles.

10 MeV LINAC STUDY

Results after the first buncher cavity

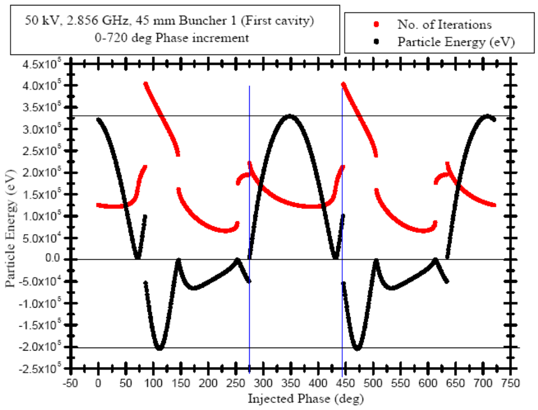

Figure 2: Plot of particle energy and No. of iterations vs injection phase for the first buncher cavity.

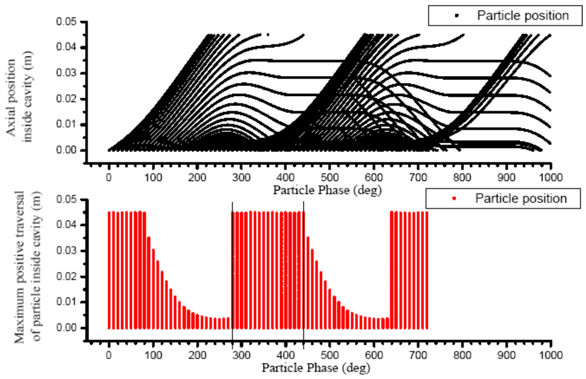

Figure 3: Plot of particle position vs phase, inside the first buncher. The top plot shows the bunching phenomenon. The bottom plot shows the maximum positive distance traversed by the particles for various injected phase.

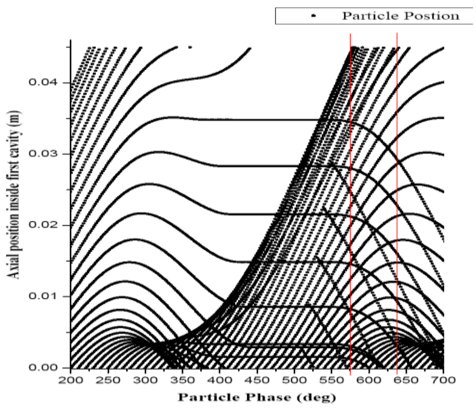

Figure 4: Plot showing bunching of particles.

47.6 % (343 out of 721) of injected 50 keV electrons are accelerated and transmitted through first RF buncher. These are particles within the injection phase 275 deg. to 440 deg. (ΔΦ = 165 degrees), see figs. 2 and 3. Out of these, only particles in the phase 275 deg to 410 deg (ΔΦ = 135 deg) are bunched to a phase width ΔΦ = 55 deg. (575 deg. to 630 deg.), see fig.4. Particles within the phase 410 deg. to 440 deg. (ΔΦ = 30 deg.) are transmitted but are not bunched. All other particles traverse up to some distance inside the cavity and are then de-accelerated and come out of the electron gun end of the cavity. The maximum electron energy in forward direction is 330 kV and in the backward direction it is 205 kV. Capture efficiency of first buncher cavity is 37.5 % (135 deg./ 360 deg.) and ΔΦoutput / ΔΦinput = 55 deg. / 135 deg. = 40.7 %.

Using the first Buncher with half the length

Using the first buncher with half the length (22.5 mm), simulations were performed and the results are:

56.4 % (407 out of 721) of injected 50 keV electrons are accelerated and transmitted through first RF buncher. These are particles within the injection phase 275 deg. to 475 deg. (ΔΦ = 200 degrees), out of 0 to 720 degrees. Only particles in the phase 275 deg to 450 deg (ΔΦ = 175 deg) are bunched to a phase width ΔΦ = 90 deg. (480 deg. to 570 deg.), see fig.4. Particles within the phase 450 deg. to 475 deg. (ΔΦ = 25 deg.) are transmitted but are not bunched. The maximum electron energy in forward direction is 330 kV and in the backward direction it is 190 kV. Capture efficiency of first buncher cavity is 48.7 % (175 deg./ 360 deg.) and ΔΦoutput / ΔΦinput = 90 deg. / 175 deg. = 51.4 %.

The energy gain by the particles as it traverses along the accelerator is shown in fig. 5. Particles within the phase 275 deg. to 450 deg. (ΔΦ = 175 deg) are accelerated, though all the particles are not having the same energy.

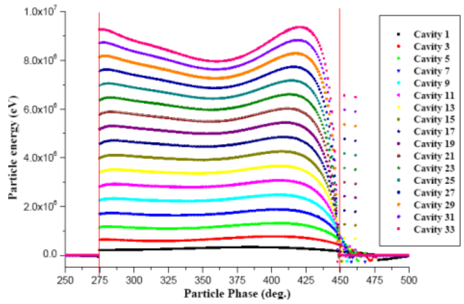

Figure 5: Plot of the particle energy (after each of the 17 accelerating cavities) versus the injected phase when at the entry of first buncher cavity.

CONCLUSIONS

The first buncher with half the length gives better electron capture efficiency than the full buncher. Calculated capture efficiencies will be lower if space charge and transverse dynamics effects are considered. The program written in FORTRAN was benchmarked and is helpful in understanding the RF bunching phenomenon.

REFERENCES

[1] Mayo and Cwiakala, "Theory and Problems of Programming with FORTRAN 77"

[2] R.B.Miller, "Electronic Irradiation of Foods".

[3] K. Irie et al, "A compact electron linac using side-coupled structure", JJAP, Vol 12, No. 2, p. 277.